AD-A054 923   ARINC RESEARCH CORP ANNAPOLIS MD   F/G 5/5

PARTITIONING MICROELECTRONIC EQUIPMENT THROUGH THE USE OF A SYM--ETC(U)

DEC 67 G H GRISWOLD, H R LEUBA   F33615-67-C-1517

UNCLASSIFIED   2930-929   NL

1 OF 1

AD A054923

END

DATE FILMED

7-78

DDC

2930-929

(4)

PARTITIONING MICROELECTRONIC EQUIPMENT THROUGH THE USE OF A SYMPTOM MATRIX

Grafton H. Griswold
ARINC Research Corporation

Aerospace Medical Research Laboratories
Aerospace Medical Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

FOREWORD

This study was initiated by the Behavioral Sciences Laboratory of the Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. The research was conducted by ARINC Research Corporation, Annapolis, Maryland, under Contract F33615-67-C-1517. Harald R. Leuba, Ph.D., and Grafton H. Griswold were the principal investigators. Mr. Gerald R. Chubb and Mr. Nilss Aume of the Systems Effectiveness Branch, Human Engineering Division, were the contract monitors. The work was performed in support of Project No. 7184, "Human Performance in Advanced Systems," and Task No. 718409, "Man-Machine Systems Research." The research sponsored by this contract was started in March 1967 and was completed in December 1967.

The author acknowledges the assistance of the research team used in this study: Mr. Donald Hobson, Mr. James Reese, and Mr. Kenneth Rhodes. Mr. Gordon Hoskins also provided a valuable service by performing the symptom analysis for the Indicator Coupler Component of the AN/ARN-85 LORAN Receiver. Special acknowledgement is also made of the contribution of Dr. A. Habayeb, who developed the material on partitioning that is included as Appendix III to this report.

This technical report has been reviewed and is approved.

Walter F. Grether, Ph.D.
Technical Director
Behavioral Science Laboratory
Aerospace Medical Research Laboratories

622-02F

ABSTRACT

The purpose of this research was to establish the requirements for human-factors data to be used in the design of microelectronics. An interdisciplinary research team projected the design considerations that will be applicable during the period 1970-1980, and on the basis of these projections, postulated that the major human-factors-data requirements will be in the area of malfunction diagnosis. A feasibility study was initiated to determine feasibility of partitioning an equipment in such a way that the malfunction symptoms can be related directly to a single or small group of replaceable assemblies. A symptom-matrix was prepared for a sample equipment (the Indicator-Coupler of the AN/ARN-85 LORAN Receiver) and then the equipment was repartitioned on the basis of the information contained in the matrix. A second matrix was prepared for the new configuration and then compared with the first matrix. It was found that the repartitioning had increased the amount of information provided by the symptom that could be used to identify the cause of the malfunction by 52 percent. It was concluded that this would reduce the number of errors that a maintenance technician would be likely to make in troubleshooting the reconfigured equipment.

CONTENTS

LIST OF SYMBOLS

H_o	Number of ordered partitions
H_n	Number of unordered partitions
$p(n)$	Number of unrestricted decompositions
$q(n)$	Number of decompositions into distinct parts
D_i	Unrestricted decompositions
$\mathfrak{S}_n^{(m)}$	Stirling Number of the second kind*
H_t	Total number of unordered partitions
$C_1 \cup C_2 \cup C_3$	Union of cells
$C_1 \cap C_2 \dots C_r$	Intersection of cells
P_1	Pins/cell C_1
h_{ij}	Number of cells in the i^{th} decomposition with j blocks
$(1,2,3,\dots n_r)$	Decomposition of r cells
[AB, CDE]	Partition (two cells with blocks A & B in one and C, D, & E in the other)
$\{N_1, N_2, N_3\}$	Pins/partition including bias and ground pins
LSI	Large-Scale-Integration (Major Component or Greater)
MSI	Medium-Scale-Integration (Assembly to minor component)
IC	Integrated Circuit

* Handbook of Mathematical Functions With Formulas, Graphs, and Mathematical Tables, U. S. Department of Commerce, National Bureau of Standards Applied Mathematical Series 55, June 1964.

LIST OF SYMBOLS(continued)

$SLPC_i$	Signal-Line-Pair-Combinations of block A_i and the remaining blocks
ISL_i	Isolated-Signal-Lines of block A_i
TSL_i	Total-Signal-Lines of block A_i

SECTION I

INTRODUCTION

Microelectronics technology is expected to play a major role in the design of Air Force systems for at least the next fifteen years. Anticipating the possibility that the effective use of microelectronics and personnel will make updated human-factors data essential for such design work, the Aerospace Medical Research Laboratories (AMRL) initiated a program, covered herein, to define requirements for human-factors research to support design analyses.

STATEMENT OF THE PROBLEM

During the design of complex microelectronic systems between 1970 and 1980, alternative design configurations will be evaluated in terms of expected performance, cost, and impact on the military posture. When system designers are evaluating alternatives associated with microelectronics, they will have to consider human-factors data. They will ask what these data are and whether the Air Force is prepared to provide them when requested. Specifically, the questions to be answered concerning the 1970-1980 period are as follows:

- What will be the state of the art of microelectronics?
- What will be the predominant maintenance philosophy?
- What will be the Air Force's system-design requirements in the human-factors field?

To answer these questions, the following specific objectives were established:

- Evaluate the adequacy of current maintainability criteria for microelectronic-equipment design
- Establish the probable advances in microelectronic technology from 1970 to 1980

- Determine human-factors research requirements relevant to maintainability design of microelectronic equipment

APPROACH

Meetings of the personnel assigned to the research team were held periodically to present findings and discuss them. At each meeting, team members were assigned specific tasks to perform before the next meeting. Through this process, important areas for consideration were identified; for one of these, the symptom matrix, a feasibility study was established. The team consisted of the following personnel:

Title	Speciality
Senior Engineer	Microelectronic devices
Senior Engineer	Maintainability (emphasis on microelectronics)
Senior Engineer	Operations research and cost-effectiveness analysis
Scientist	Human-factors and operations research

In the periods between meetings, the team members reviewed documents related to their areas of specialization and to the problem at hand. These documents included military standards, specifications, and regulations; human-factors handbooks; and research reports on the current and future state of the art.

The objectives of the review were to define the current status of the related disciplines, determine trends in their development, and provide a basis for projecting conditions during the period 1970-1980. A further purpose of the review of human-factors handbooks was to establish their adequacy for

use in cost-effectiveness trade-offs by designers of microelectronic equipment.

On the basis of the information obtained from document reviews and the conclusions reached at the meetings, the configuration of microelectronic equipment and the general maintenance philosophy were projected for the period 1970-1980. These projections were the basis for determining the human-factors research requirements.

Projected Microelectronic-Equipment Configuration

The principal guide to how microelectronic equipment will be configured is the DoD memorandum, Policies for use of Microelectronics in Military Systems and Equipment, 14 April 1967. This memorandum states, "Microelectronic circuits shall be packaged into discrete replaceable modules of such cost and reliability that disposal-on-failure rather than module repair is the most effective and economical logistic support action." Because of the predicted high reliability and low cost per circuit function for microcircuit devices in the 1970s, these throwaway modules may be as complex (functionally) as the components of present systems.

In addition to being modular at fairly high levels of functional complexity, the microelectronic equipment will be more complex than its present equivalent. System designers will take advantage of the decreased size, weight, and circuit cost, and the increased reliability to make their equipment more sophisticated. In addition, it will be economically feasible to devote more of the circuitry to self-test capability and other troubleshooting aids.

These factors will result in equipment that is smaller, more dense, and more complex functionally, and has good performance-monitoring and self-test capability. Although

the equipment will be more complex, the lowest level of replacement will be at a relatively high functional level, reducing the number of choices facing the diagnostician. It is believed that the mechanical configuration will be essentially the same as that of present equipment that has been designed for ease of maintenance (module replacement).

Maintenance Philosophy

On the basis of the projected configuration of microelectronic equipment during the 1970s, the DoD policy for use of microelectronics, and the present trends in the maintenance of Air Force equipment, the following maintenance philosophies are foreseen for the flight-line, shop, and organizational levels for the priod 1970-1980:

- Flight Line. Maintenance will consist of performance verification and interchange of component "black boxes." Performance will be verified by either built-in provisions or automatic checkout equipment, employing essentially a go/no-go indication. Faulty equipment will be corrected by interchanging major components or complete equipments. Some alignment or adjustment may be required, but it should be less frequent and less complex than at present.

- Shop. Maintenance will consist of finding a failed module* in a component. Automatic test equipment, including a module tester, will probably be evailable. Module access and removal will be facilitated by mechanical design that permits the use of simple tools

* The replaceable modules will be of a size and complexity to permit economical discard upon failure; i.e., the purchase and stocking costs for the module will be less than or equal to the cost to repair the module and stocking the necessary spare parts.

and requires only a low level of dexterity. Equipment will make greater use of digital circuitry, necessitating a logical approach to troubleshooting where complete automatic test equipment is not available. The requirement for alignment will be greatly reduced, and where it is still necessary, interactions and extreme sensitivities will not be evident.

Supply procedures will be relatively simple, with desired replacements readily available. The availability of spare modules will be critical to maintaining the equipment operational and may be met by building the spares into the equipment or by initially supplying sufficient spares to maintain the equipment for its planned life.

The use of new types of testing devices (infrared scanner, fiber optics, etc.) may require special training; but, overall, less training should be required. The technical information required will be less complex and will be presented in such a way that it can be used efficiently by the maintenance personnel. (A data source is currently being developed that uses a microfilm projector with access to desired information through coded keys. Aural instructions from magnetic tape will also be used to strengthen the visual presentation.)

- <u>Organizational (fixed ground equipment)</u>. Maintenance will consist of a combination of the tasks described for the flight-line and shop levels. Fairly large components will be interchanged on the operating equipment to maintain good availability. The components will be repaired by the same organization through module replacement. Built-in redundancy and switching

will allow "batching" of maintenance actions. Preventive maintenance for electronic equipment will be practically eliminated.

Feasibility Study

During the study, we determined that the design of equipment for easy fault location required research. The development of a procedure for partitioning an equipment so that the malfunction symptoms would be related directly to a small group of assemblies was suggested. However, we were not certain such a configuration could be accomplished within such system constraints as electrical isolation and a minimum of interconnections. We decided to perform a trial application, or feasibility study, before recommending that a large-scale research program be established to develop such a technique.

The feasibility study consisted of developing a matrix of symptom versus cause (failed part) for a representative microelectronic equipment, and then attempting to repartition the equipment on the basis of this information so that the causes of each symptom or group of symptoms would be located on one or a small number of replaceable assemblies. Constraints placed on the repartitioning were (1) that there could be no significant increase in the number of interconnections, and (2) that circuits which were not electronically compatible could not be placed on the same assembly. Section II covers the feasibility study. The conclusions produced by both the main study and the feasibility study are presented in Section III.

SECTION II

INVESTIGATION OF SYMPTOM-MATRIX APPROACH TO PARTITIONING

RATIONALE

A previous ARINC Research study* suggested an approach to improving the troubleshooting capability of the maintenance technician. This approach was to develop a matrix of malfunction symptom versus probable cause (part failure) for an equipment. The technician would use this information to determine the most probable location of a failure when presented with a particular set of symptoms. It was hypothesized that this troubleshooting strategy would be enhanced if the equipment were partitioned so that all the causes for each malfunction symptom were located in one or a few replaceable assemblies.

Since microelectronic equipment will be modularized at a high level of functional complexity, and the discard-at-failure maintenance philosophy will be emphasized, the symptom-matrix approach to partitioning this equipment should be quite effective. However, it was necessary to investigate this theory further because other design constraints may limit the extent to which this approach can be implemented. An additional problem is that different failure modes for a particular part may cause different symptoms, but obviously this part cannot be located in two different assemblies. It was decided, therefore, to perform a feasibility study of the approach before recommending that a research program be established.

---

* The Symptom Matrix - An Analytical Tool for Evaluating System-Maintenance Checkout Procedure, H. R. Leuba, 16 April 1962, ARINC Research Publication 4607-1-294.

TECHNICAL APPROACH

The feasibility study consisted of the following tasks:

1. Select research vehicle
2. Prepare symptom-matrix
3. Partition equipment
4. Prepare new matrix
5. Compare matrices

The AN/ARN-85 LORAN C/D Receiving Set was selected as the research vehicle because it is predominantly microelectronic and because complete technical data were available. However, to limit the analysis to the amount of effort available for this study, only the Indicator-Coupler component of the AN/ARN-85 was analyzed in detail. The AN/ARN-85 consists of six components:

<u>Antenna Coupler</u>, which matches the receiver to the antenna while providing r-f gain and automatic notch rejection.

<u>Receiver</u>, which automatically acquires, tracks, and measures the time differences of the LORAN-C/D signals, while automatically rejecting jamming and random noise interference. The time-difference data are sent to the Mark XIV computer and the control indicator.

<u>Mark XIV Computer</u>, which automatically transforms the hyperbolic time differences into present-position and guidance information. This information is then routed to the control indicator and indicator coupler.

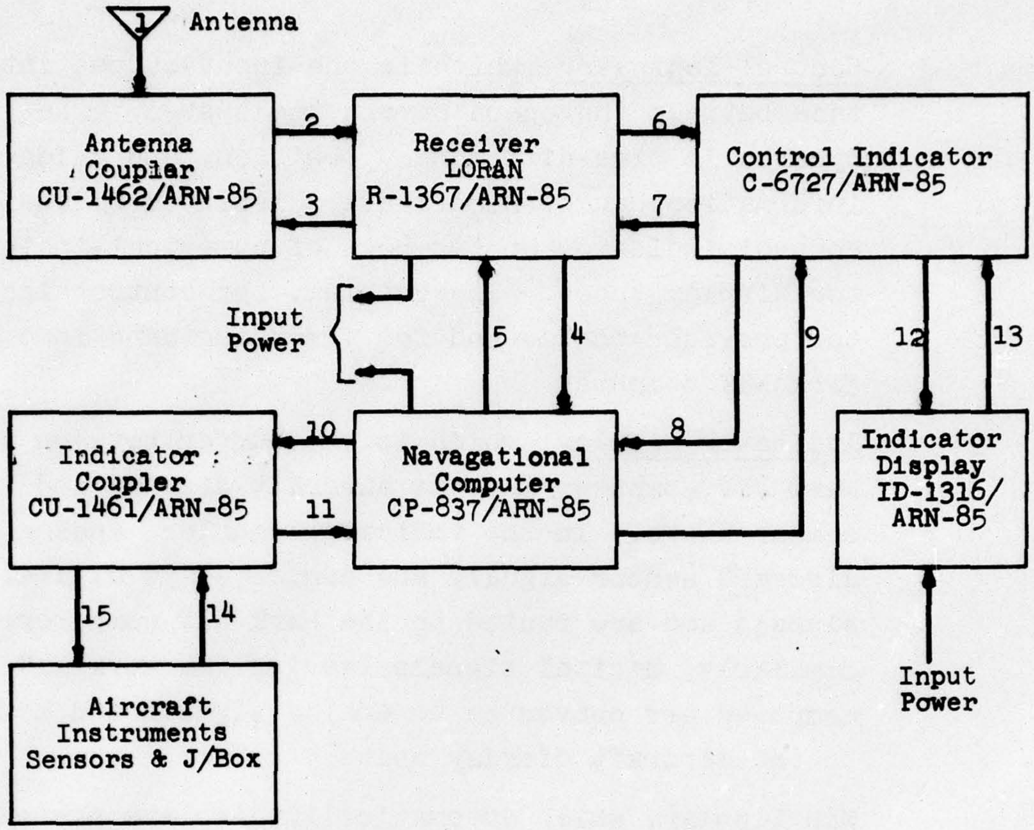
Control Indicator, which is the input-output interface between the operator and the system. The hyperbolic time-difference, position, and guidance information can be numerically displayed by the control indicator on two rows of numerical-indicator display tubes. In addition, the control indicator provides the method for inserting data into the Mark XIV computer.

Indicator Coupler, which is the buffer between the Mark XIV computer and the aircraft display and sensor units. In the indicator coupler, analog aircraft sensor signals are converted to digital signals and are routed to the Mark XIV computer. Similarly, digital signals leaving the Mark XIV computer are converted to analog signals and sent to the aircraft display units.

Map Display, which automatically displays present position and past track on conventional charts. A pickle switch, controlled by the operator, provides a method for marking the chart to record present position.

The components of the receiver set are connected to produce the flow of information as indicated in Figure 1. The antenna receives signals from two stations, a master and a slave, with a known coding delay between them. The receiver detects these signals and provides them to the computer, which derives position information. The control indicator and the indicator coupler provide interfaces between the receiving set and aircraft instruments and displays.

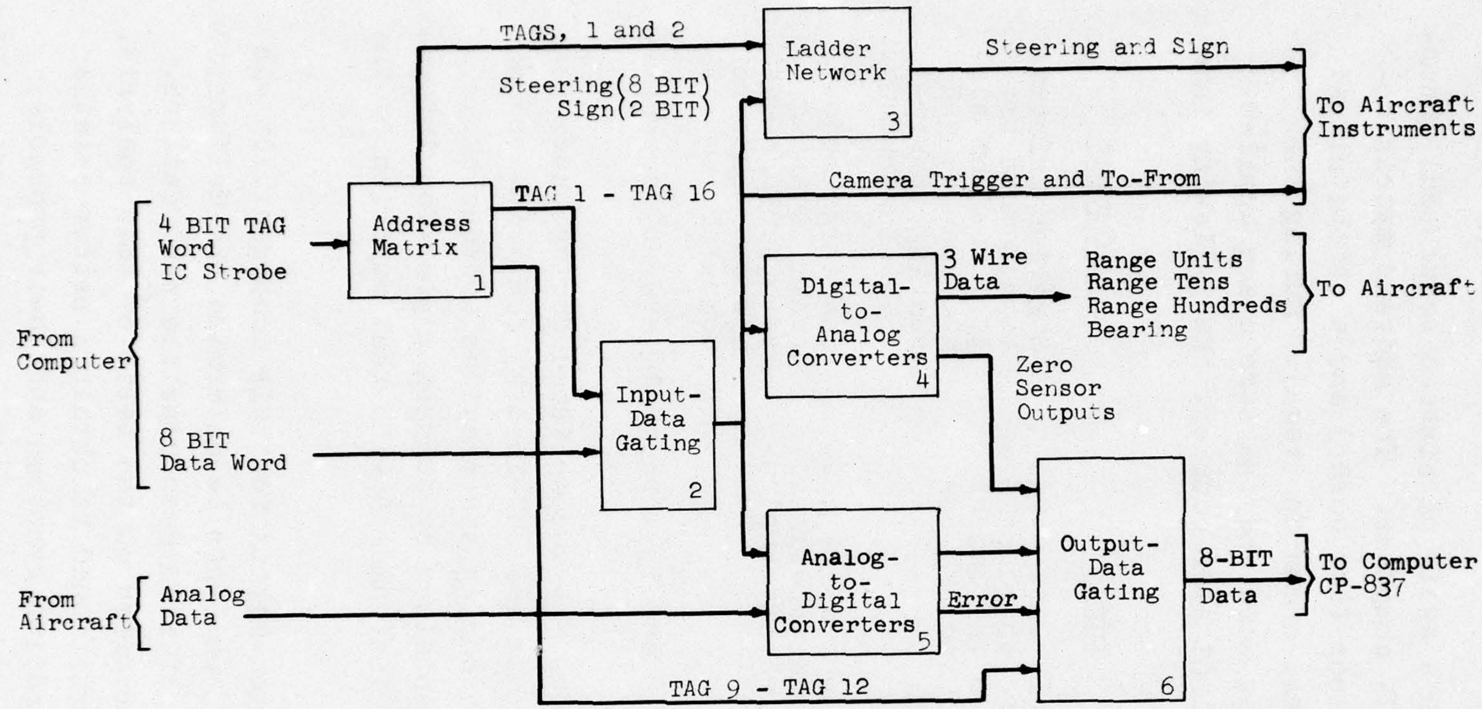
The indicator coupler consists of six functional areas as indicated in Figure 2. This unit operates on a



1 - LORAN r-f signals
2 - Amplified analog r-f signal
3-- Control commands, power
4 - Time differences, timing and interrupt waveforms
5 - Velocity assist, computer malfunction, LORAN, not available
6 - Time-difference information, power
7 - Mode, basic rate, start TD (time differences)
8 - Inserted data, control positions, data #13
9 - Display data, data for #12, power
10 - Steering, range/bearing
11 - Heading, airspeed, course
12 - Latitude, longitude, cosine latitude, computer malfunction
13 - Scale, shift-left command
14 - Heading, airspeed, course - analog
15 - Steering, range/bearings - analog

FIGURE 1

AN/ARN 85 LORAN SIGNAL FLOW BLOCK DIAGRAM



Note:
Each functional block is composed of the following circuit cards (replaceable assemblies):

1 - A1, P/O A3, and P/O A9

2 - P/O A3, A8, and P/O A9

3 - A4 and A6

4 - A10, P/O A12, and P/O A13

5 - A5, P/O A7, P/O A9, A11, P/O A12 and P/O A13

6 - A2, P/O A7, and P/O A9

FIGURE 2

INDICATOR COUPLER (CU-1461), OVERALL BLOCK DIAGRAM

time-sharing basis with a cycle of sixteen sequential interrogations by the Mark IV computer. The address matrix accepts these interrogations (tag words) and a strobe signal, and it generates internal commands (tags). During the intervals in which a tag word and the strobe are applied simultaneously to the indicator coupler, the following inputs and outputs are supplied:

Tag	Input	Output
1 through 4	Eight-bit data words from the computer are gated to the ladder network and the converters.	Steering information camera trigger, to-from signal, range, and bearing to aircraft instruments.
9 through 12	Course and drift analog representations from aircraft instruments.	Operating modes, range, bearing, zero sensors, and error outputs to computer.

(Note: Tags 5 through 8 and 13 through 16 are not currently used).

The necessary conversions are accomplished during these tag intervals and zero outputs are obtained by comparing the new data with data supplied during the previous address cycle. The error outputs are obtained by comparing position information from the aircraft instruments with that supplied by the Mark IV computer.

To prepare a symptom-matrix for this component, it was necessary to perform an analysis to determine the malfunction symptom that would result from each possible part failure. After the matrix was prepared on the basis of this analysis, the component was repartitioned to obtain a better relationship between the malfunction symptoms and their probable causes. Another matrix was prepared for the new configuration

and compared with the first matrix to measure the improvement.

These tasks are described in greater detail below.

Symptom Analysis

The basic approach to the symptom analysis was to assume a failure of each part and then synthesize the resulting malfunction symptoms by analyzing the effect of the part failure on the operation of the circuitry. The part-failure modes were based on past experience for standard electronic parts and on circuit analysis of the micrologic (μL) devices. A failure rate was then assigned to each part-failure mode, as illustrated in Table I.

TABLE I

FAILURE RATE
(Number of Failures Per Million Hours)

Part Type	Open	Short	Failure Modes; Flip-Flop Outputs (Pins 7 and 9) Fixed			
			One/ Zero	One/ Zero	One/ Zero	One/ Zero
Micrologic (μL):						
Buffer	0.060	0.040				
2-input NAND	0.030	0.020				
3-input NAND	0.030	0.020				
Flip-Flop			0.035	0.035	0.015	0.015
Capacitor	0.004	0.006				
Diode	0.015	0.035				
Resistor, Fixed	0.010					
Resistor, Variable	1.000					
Transistor	0.040	0.060				

The failure rate for micrologic devices was assumed to be 0.10 failure per million hours ($F/10^6$ hr). This failure rate is based on data presented in the NASA Microelectronic Device Data Handbook (NASA publication NPC-275-1) as being representative of the quality of microelectronic devices to be produced during the 1970s. The relative probabilities for each failure mode were derived from the number of possible internal failures that would cause these modes. The main failure causes considered were open bonds, surface shorts, and discontinuities in the semiconductor substrate. The failure rates for the remaining electronic parts were obtained from MIL-HDBK-217 with relative frequency of occurrence of failure (open or short) modes based on the past experience of the experimenters.

The next step in the symptom analysis was to determine the range of possible malfunction symptoms that the Indicator Coupler could exhibit. Since the research vehicle was not a complete operating equipment, the symptoms were based on the effects of a failure of the Indicator Coupler on the associated components. There are two groups of outputs from the coupler: one goes to a computer and the other to the aircraft instruments. The outputs to the computer consist of an eight-bit data word, and the outputs to the instruments are range, bearing, steering deviation, camera trigger, and to-from signals. An error in these signals was assumed to require recognition either by the computer or a human operator for an equipment failure to occur. (From an operational standpoint, an equipment failure does not occur until it has been discovered.) Therefore, the basic symptoms established for this study were errors in any one of the data bits to the computer (register positions) or in any one of the signals to the aircraft instruments.

Each part in the indicator was assumed to fail in the modes listed in Table I, and the results of these failures were interpreted in terms of the malfunction symptoms described above. Figure 3 shows one of the data sheets resulting from this analysis. The data were summarized in matrix form of part failures versus malfunction symptoms, with failure rates noted at the intersections. (See Appendix I of this report). The matrix was then summarized by replaceable assembly as shown in Table II (A). In Table II, the probabilities are conditional; i.e., given a particular symptom, what is the probability that the cause is located in a specific assembly?

Partitioning

The symptom-matrix developed for the Indicator Coupler provided the information necessary to repackage the component for easy fault location. The optimum configuration for this purpose would be to put all the parts related to a particular symptom in the same assembly. However, this is not possible, because assemblies would not be uniform in complexity and many parts are related to more than one symptom. Additionally, other equipment constraints such as electronic compatibility, number of interconnections and cost of modules (for throw-away maintenance) would not be met. Therefore, tradeoffs must be made to arrive at an acceptable configuration.

The reconfiguration of the Indicator-Coupler component of the ARN-85 was based on the use of assemblies (circuit cards) of approximately the same complexity as that of currently used assemblies. These assemblies are small enough to be discarded economically at the circuit costs and reliabilities projected for the 1970s, and their use facilitates the comparison of the new configuration with the original one. An economical discard situation is one in which the cost of

SYMPTOM-OF-FAILURE ANALYSIS

Equipment: AN/ARN-85 LORAN Receiving Set — Sheet 2 of 12

Component: CU 1461/ARN-85 Indicator Coupler — Module Card A2

Part Reference	Part Type	Part Failure Mode	Failure Rate (Failures Per 10^6 hrs.)	Symptom of Failure
A5A1	μL Buffer	Open	0.060	Incorrect Steering Deviation
		Short	0.040	Incorrect Steering Deviation
A3A4-9	μL Two-Input NAND Gate	Open	0.030	Incorrect To-From Signal Incorrect Steering Deviation Incorrect Camera Trigger
		Short	0.020	Same as for Open Mode
A4A2	μL Buffer	Open	0.060	Incorrect Register Indications in Positions 1, 2, 3, 4, 7, & 8
		Short	0.040	Incorrect Register Indications in Positions 1 through 8
A1A1-4	μL Two-Input NAND Gate	Open	0.030	Incorrect Register Indications in Positions 1 through 8
		Short	0.020	Incorrect Steering Deviation Incorrect To-From Signal Incorrect Camera Trigger Incorrect Range (units, tens, and hundreds) and Bearing Incorrect Register Indications in Positions 1, 2, 3, & 4

FIGURE 3

SAMPLE SYMPTOM-ANALYSIS FORM

TABLE II

SYMPTOM MATRIX FOR INDICATOR COUPLER
(Probability of a Card Failure Given a Symptom)

Card Type	Symptom														
	Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing
	(A) Original Configuration														
A1	0.318	0.311	0.307	0.311	0.299	0.293	0.296	0.295	0.586	0.869	0.074	0.216	0.216	0.216	0.203
A2	0.046	0.047	0.036	0.055	0.049	0.047	0.032	0.035							
A3	0.059	0.063	0.077	0.078	0.063	0.067	0.064	0.063	0.414	0.131	0.066	0.049	0.049	0.049	0.046
A4											0.186				
A5			0.264	0.267	0.268	0.285									
A6											0.674				
A7	0.254	0.267					0.272	0.271							
A8												0.038	0.038	0.038	0.036
A9	0.049	0.023	0.031		0.031		0.210	0.209				0.057	0.057	0.057	0.054
A10												0.436	0.436	0.152	
A11			0.224	0.226	0.227	0.242	0.064	0.063							
A12	0.215	0.226												0.284	0.517
A13	0.060	0.063	0.063	0.063	0.063	0.067	0.064	0.064				0.205	0.205	0.205	0.144
	(B) New Configuration														
A1	0.318	0.311	0.307	0.311	0.299	0.293	0.296	0.295	0.586	0.869	0.074	0.216	0.216	0.216	0.203
A2	0.045	0.047	0.036	0.055	0.049	0.047	0.032	0.035							
A3	0.059	0.063	0.077	0.781	0.063	0.067	0.064	0.063	0.414	0.131	0.066	0.049	0.049	0.049	0.046
A4											0.186				
A5			0.550	0.555											
A6											0.674				
A7							0.566	0.565							
A8												0.678			
A9	0.049	0.023	0.031		0.031		0.210	0.209				0.057	0.057	0.057	0.054
A10													0.678		
A11					0.558	0.594									
A12	0.529	0.557													
A13														0.678	
A14															0.697

the replacement is equal to or lower than the cost of repairing the failed assembly.

The basic approach to repartitioning was to look for natural circuit groupings in the matrix that were related predominantly to a particular malfunction symptom or group of symptoms and to put these circuits in the same assembly. The design of the component was such that a number of circuit groupings existed that were primarily related to a particular type of symptom. By rearranging these circuits according to symptoms, the number of interconnections was reduced, while the relationship between the symptoms and the location of their causes was made more direct. The circuit groupings for the new configuration were selected on the basis of obvious relationships between circuit functions and malfunction symptoms. They do not necessarily represent the optimum configuration that would result from an exhaustive analysis of all possible combinations. The parts that make up each assembly of the new configuration are listed in Appendix II. Table II (B) shows the symptom-matrix resulting from the new configuration. (Because circuit cards A1-A4 were closely related to a group of symptoms or a unique symptom, they were left unchanged in the reconfiguration).

Comparison of Matrices

The symptom matrices developed for the current configuration and the revised configuration were compared by two different techniques. The efficiency of information transfer from symptom to assembly failure was computed, and the expected troubleshooting efficiency was calculated for each design.

Information Transfer

The symptom/failure matrix is a stimulus/response frequency table, as discussed by Attneave*: the symptom is the stimulus; the failed part (or assembly) is the response. By increasing the amount of information about the failure that is gained by knowledge of the symptom, troubleshooting should be made more accurate. To measure the information transfer, the following functions were computed:

$\hat{H}(s)$ = estimated average information in the occurrence of symptom (out of m possible symptoms)

$$= \sum_{i=1}^{m} \hat{p}(s_i) \log_2 \frac{1}{\hat{p}(s_i)} \qquad (1)$$

where

$\hat{p}(s_i)$ = relative probability of occurrence of symptom i

$$= \frac{N(s_i)}{\sum_{i=1}^{m} N(s_i)}$$

and

$N(s_i)$ = Number of occurrences (or rate of occurrence) of symptom (i).

$\hat{H}(f)$ = estimated average information in the occurrence of a failure (out of n possible failures)

$$= \sum_{j=1}^{n} \hat{p}(f_j) \log_2 \frac{1}{\hat{p}(f_j)} \qquad (2)$$

---

* Fred Attneave, Application of Information Theory to Psychology, Henry Holt and Co., pp. 42 ff.

where

$$\hat{p}(f_j) = \text{relative probability of occurrence of failure } j$$

$$= \frac{N(f_j)}{\sum_{j=1}^{n} N(f_j)}$$

and

$N(f_j)$ = Number of occurrences (or rate of occurrence of failure).

$\hat{H}(s,f)$ = estimated average information in the joint occurrence of symptom and failure

$$= \sum_{i=1,j=1}^{m,n} p(s_i,f_j) \log_2 \frac{1}{p(s_i,f_j)} \tag{3}$$

where

$\hat{p}(s_i,f_j)$ = relative probability of joint occurrence of symptom (i) and failure (j)

$$= \frac{N(s_i,f_j)}{\sum_{i=1,j=1}^{m,n} N(s_i,f_j)}$$

and

$N(s_i,f_j)$ = Number of joint occurrences (or rate of joint occurrence) of symptom (i) and failure (j)

$T(s;f)$ = estimated information transmitted from symptom to failure

$$= \hat{H}(s) + \hat{H}(f) - \hat{H}(s,f) \tag{4}$$

$$E(T) = \text{estimated efficiency of transmission}$$

$$= \frac{\hat{T}(s;f)}{\hat{H}(f)} \tag{5}$$

The information transfer, then, is the overlap of the information given by the symptom and the information given by the failure. It can therefore be considered as a measure of correlation between symptom and failure. In the symptom/failure matrix, the greater the concentration of frequencies of symptom/failure occurrence, the greater the correlation -- and thus the greater the information transfer -- between symptom and failure. The efficiency is the ratio of the amount of transferred information to the total amount that could be transferred.

Two simple examples of symptom/failure matrices are given below. In the first, there is very little correlation between symptom and failure; in the second, the correlation is high. This fact is established by measuring the information transfer, using Equations 1 through 5.

	S_1	S_2	S_3	S_4
f_1	4	3	2	1
f_2	3	3	2	2
f_3	4	2	2	2

Equipment 1

	S_1	S_2	S_3	S_4
f_1	5	4	1	0
f_2	2	1	2	5
f_3	0	2	5	3

Equipment 2

In Equipment 1, Equation 1 yields

$$\hat{H}(s) = \sum_i \hat{P}(s_i) \log_2 \frac{1}{\hat{P}(s_i)}$$

$$= \frac{11}{30} \log_2 \frac{30}{11} + \frac{8}{30} \log_2 \frac{30}{8} + \frac{6}{30} \log_2 \frac{30}{6} + \frac{5}{30} \log_2 \frac{30}{5}$$

$$= 0.531 + 0.508 + 0.465 + 0.432 = 1.936 \text{ bits}$$

Equation 2 yields

$$\hat{H}(f) = \sum_j \hat{P}(f_j) \log_2 \frac{1}{\hat{P}(f_j)}$$

$$= \frac{10}{30} \log_2 \frac{30}{10} + \frac{10}{30} \log_2 \frac{30}{10} + \frac{10}{30} \log_2 \frac{30}{10} = 1.585 \text{ bits}$$

Equation 3 yields

$$\hat{H}(s,f) = \sum_{i,j} \hat{P}(s_i,f_j) \log_2 \frac{1}{\hat{P}(s_i,f_j)}$$

$$= \frac{4}{30} \log_2 \frac{30}{4} + \frac{3}{30} \log_2 \frac{30}{3} + \frac{30}{4} \log_2 \frac{30}{4} + \ldots$$

$$+ \frac{2}{30} \log_2 \frac{30}{2}$$

$$= 3.50 \text{ bits}$$

Combining these results by the use of Equation 4 yields

$$\hat{T}(s;f) = \hat{H}(s) + \hat{H}(f) - \hat{H}(s,f) = 1.936 + 1.585 - 3.50$$

$$= 0.02 \text{ bit}$$

For equipment 2, Equations 1 through 4 yield the following:

(1) $$\hat{H}(s) = \frac{7}{30} \log_2 \frac{30}{7} + \frac{7}{30} \log_2 \frac{30}{7} + \frac{8}{30} \log_2 \frac{30}{8} + \frac{8}{30} \log_2 \frac{30}{8}$$

$$= 2.005 \text{ bits}$$

(2) $\hat{H}(f) = \frac{10}{30} \log_2 \frac{30}{10} + \frac{10}{30} \log_2 \frac{30}{10} + \frac{10}{30} \log_2 \frac{30}{10}$

$= 1.585$ bits

(3) $\hat{H}(s,f) = \frac{5}{30} \log \frac{30}{5} + \frac{2}{30} \log \frac{30}{2} + \ldots$

$= 3.12$ bits

(4) $\hat{T}(s;f) = 2.005 + 1.585 - 3.12$

$= 0.47$ bit

The efficiency of transfer, E(T), for the first equipment is 1.4 percent (0.02/1.585) and for the second equipment, 29.4 percent. These examples show that when symptoms are more highly correlated with failures, more information about the failure is gained by knowledge of the symptom. Given a symptom, a maintenance technician probably would troubleshoot Equipment 2 with fewer errors than he could Equipment 1.

In the symptom matrix for the Indicator Coupler as it is currently configured, the amounts of information available and transferred are as follows:

$$\hat{H}(s) = 3.626 \text{ bits}$$

$$\hat{H}(f) = 3.322 \text{ bits}$$

$$\hat{H}(s,f) = 5.727 \text{ bits}$$

$$\hat{T}(s;f) = \hat{H}(s) + \hat{H}(f) - \hat{H}(s,f) = 1.221 \text{ bits}$$

$$E(T) = \frac{1.221}{3.322} = 36.8 \text{ percent}$$

With the revised configuration, the figures are as follows:

$$\hat{H}(s) = 3.626 \text{ bits}$$

$$\hat{H}(f) = 3.387 \text{ bits}$$

$$\hat{H}(s,f) = 5.158 \text{ bits}$$

$$\hat{T}(s;f) = 1.855 \text{ bits}$$

$$E(T) = \frac{1.855}{3.387} = 54.8 \text{ percent}$$

The increase in information transmission was 0.634-bit, a 52 percent increase.

Efficiency of Troubleshooting

The preceding discussion shows a way of measuring the correlation between symptom and failure, but it does not give a direct measure of the efficiency of troubleshooting. Troubleshooting can be accomplished by removing the most likely failed item and replacing it with one known (or at least supposed) to be good. If the replacement does not clear the symptom, the next most likely item is replaced, and so on until the symptom is cleared.

If $p(f_j|s_i)$ = probability that the j^{th} unit is failed, given the i^{th} symptom, then the average number of trials to clear the i^{th} symptom will be

$$\sum_{j=1}^{n} j p(f_j|s_i) \qquad (6)$$

where the subscript j is the rank of the unit in the trouble-shooting sequence for s_i. If $p(s_i)$ = the relative likelihood of symptom s_i, then the average number of trials for trouble-shooting all symptoms is T_{avg} =

$$\sum_{i=1}^{m} \sum_{j=1}^{n} p(s_i)\, j p(f_j|s_i) \qquad (7)$$

where j is the rank within the n_i parts possible under symptom s_i.

It is convenient to define troubleshooting efficiency as the inverse of the average number of trials required. Thus if the first trial is always successful, efficiency is 100 percent, and the more trials required, the lower the efficiency. The troubleshooting efficiency achieved by applying the symptom matrix to the Indicator Coupler at its present configuration is 43.6 percent (expected number of trials = 2.293). By revising the arrangement of some of the parts, (new configuration), troubleshooting efficiency was raised to 59.2 percent (expected number of trials = 1.688). This represents a reduction of 46.8 percent in the average number of false trials (1.293 to 0.688). For other troubleshooting strategies, the likelihood of making unnecessary checks and/or misinterpreting the results of a check should be less, thereby decreasing the number of checks made.

APPLICATION PROCEDURE

The first step in partitioning an equipment for easy fault location is to perform an analysis to determine the symptom that will occur when each part (microelectronic device) or circuit fails. The next step is to determine the desired complexity of the replaceable modules, and the last step is to group the parts into modules or groups of modules so that there is a close relation between symptoms and the locations of their causes.

The method for performing the symptom analysis is described in detail on page 13. The complexity of replaceable modules must be based on the selected maintenance philosophy.

If a discard-at-failure maintenance policy is to be used, the cost of the replaceable module should be equal to or less than the cost of repair. In determining the repair costs, all additional facilities, equipment, and personnel required to provide the repair capability must be considered, as well as the cost of maintaining a supply of replaceable parts.

The actual partitioning of the microcircuits into modules is the most complex step in applying this technique because there are many competing constraints and because different failure modes of the same circuit can produce different symptoms. One method of attacking this problem is to use the model described in Appendix III to determine all feasible combinations of circuits to form modules of a specified size within selected constraints. Although the major constraint used in the model is a minimum of interconnections, we believe that this approach can be developed further to include other system constraints, such as radio-frequency interference (RFI), thermal dissipation, and standardization. Note that the procedure presented in Appendix III was not used to partition the study vehicle but is referenced here as a possible method for handling a more complex equipment.

Once the feasible configurations (module partitions) have been determined by such a process, the optimum configuration can be selected by calculating the amount of information transferred from the description of the symptoms to the location of the causes. The procedures for calculating this value are given under "Comparison of Matrices" (Equations 1-4). The configuration providing the maximum information transfer will require the minimum diagnostic time.

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The implementation of the DoD policy memorandum on the use of microelectronics in military equipment will direct the character of electronic maintenance towards disposal at failure of fairly complex (functionally) assemblies. This will probably be true for all types of equipment, but the increased reliability and reduced cost per function obtainable through the application of microelectronic devices will make this approach even more attractive. The advent of disposal-at-failure maintenance (DAFM) will change the skill requirements for maintenance technicians because many of the detailed tasks (complex disassembly, replacing soldered-in parts, etc.) will be eliminated. The change to microelectronics will also permit increased sophistication of equipment, thus increasing the diagnostic load on the technician. It is necessary, therefore, to investigate the impact of the changes on the selection and training of maintenance personnel.

The problem of locating the cause of system or equipment failures can be simplified by using built-in or external capability for automatic fault location, and by packaging the equipment in a manner that facilitates fault location. The symptom-matrix approach described in this report appears to be a feasible method for improving the partitioning of equipment for ease of maintenance. This approach will ease the diagnostic load on the technician and, if automatic test is used, will reduce the complexity of the automatic test equipment (the number of failure paths that the equipment must check will be reduced). The symptom-matrix approach provides information for assisting the maintenance technician during fault diagnosis; it also appears to reduce the number of interconnections between

replaceable units. This reduction in interconnections should increase equipment reliability and reduce manufacturing and test costs. It is emphasized that this approach (symptom matrix) is not necessarily limited to microelectronic equipment.

The general conclusion of this study is that the advent of microelectronic equipment will have a significant impact on the maintenance of electronic systems, and that the symptom-matrix approach to partitioning merits further investigation as a tool for enhancing the maintainability of such systems.

RECOMMENDATIONS

On the basis of the conclusions reached during this study, the following research tasks are recommended (in order of priority):

- A continuation of this study to validate the conclusions reached concerning the application of the symptom matrix. This would be accomplished by comparing fault-location times on the existing equipment (AN/ARN-85 Indicator Coupler) with those for an equipment modified to simulate the new configuration.
- A study to develop further the symptom-matrix approach to partitioning. This study should consider a range of system constraints (RFI, thermal, mechanical, etc.) and a cross section of equipment classes.
- A study to determine the optimum course content for maintenance personnel for microelectronic equipment. The prime consideration should be the emphasis on system interactions and troubleshooting strategies, and and the de-emphasis of electronic theory.
- An investigation of the application of new technology for use in fault diagnosis (infrared, fiber optics, holography).

APPENDIX I

SYMPTOM MATRIX FOR THE INDICATOR COUPLER COMPONENT OF THE AN/ARN-85 LORAN RECEIVING SET

INTRODUCTION

This appendix presents the symptom matrix that was developed at the part level for the original and revised configurations of the study vehicle. The information contained in this matrix was summarized at the replaceable-assembly (circuit card) level and presented in Table II in the body of this report.

EXPLANATION OF ENTRIES

Symptoms

The symptom-matrix entries under the heading "Symptom" indicate the effect on each of the Indicator-Coupler outputs that can result from a part failure. It is assumed that a failure will not be noted until an error in one or more of the outputs is detected by either the associated components or the operator.

Part Numbers

The parts are identified by conventional military symbols, except for the microelectronic devices that are prefixed "UL". The four digits after the "UL" indicate the position of the device on the original circuit board, and the dash indicates the output pin number when the device contains more than one circuit.

Failure Rates

The values indicated at the intersections in the matrix are failure rates in number of failures per million hours. The failure rates indicate the number of times in a million hours

of equipment operation that a failure of a specific part will cause a particular symptom. To determine the probability that a specific part has failed, given a particular symptom, the failure rate noted at the matrix intersection is divided by the sum of all failure rates associated with that symptom.

Part Number	Symptom															
	Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
	CARD A1															
ULA5A1											0.10					0.10
ULA4A1-9											0.05					0.05
ULA4A4									0.10	0.10	0.10					0.10
ULA3A4-9									0.05	0.05	0.05					0.05
ULA4A2	0.10	0.10	0.10	0.10	0.04	0.04	0.10	0.10								0.10
ULA3A4-4	0.10	0.10	0.10	0.10	0.06	0.06	0.10	0.10								0.10
ULA5A5	0.10	0.10		0.10	0.10	0.10										0.10
ULA5A3-9	0.05	0.05		0.05	0.05	0.05										0.05
ULA3A3	0.10		0.10		0.10		0.10	0.10								0.10
ULA3A1-4	0.05		0.05		0.05		0.05	0.05								0.05
ULA4A5	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10								0.10
ULA3A5-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
ULA4A3	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10								0.10
ULA3A5-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
ULA3A1-4	0.05	0.05	0.05	0.05					0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
ULA3A1-9	0.05	0.05	0.05	0.05					0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
ULA3A2-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
ULA3A2-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
ULA2A1-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
ULA2A1-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
ULA2A2-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
ULA2A2-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
ULA3A3-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
ULA3A3-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
ULA2A3-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05			0.05					0.05
ULA2A3-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05			0.05					0.05
ULA2A404	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02	0.05
ULA2A4-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02	0.05
ULA2A5-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02					0.05
ULA2A5-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.03	0.03	0.05	0.05	0.05	0.05	0.05
ULA1A1-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.05
ULA1A2-4	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03			0.02					0.05
ULA1A3-4	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05
ULA1A4-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05
ULA1A5-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
ULA1A5-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
ULA1A1-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.03	0.03	0.03	0.05
ULA1A2-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.03	0.05	0.03	0.03	0.03	0.03	0.05
ULA1A3-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.05	0.02	0.02	0.02	0.02	0.05
ULA1A4-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02	0.05
CR5	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
CR4	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
CR3	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015			0.015	0.015	0.015	0.015	0.015	0.015
CR2	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
	CARD A2															
ULA2A1-4	0.05															0.05
ULA1A1-9	0.05															0.05
ULA2A1-9	0.05															0.05
ULA3A1-4	0.05															0.05
ULA5A2	0.10															0.10
ULA2A2-4		0.05														0.05
ULA2A2-9		0.05														0.05
ULA1A-4		0.05														0.05
ULA3A1-9		0.05														0.05

(continued)

Part Number	Symptom															
	Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
	CARD A2 (continued)															
ULA4A2		0.10														0.10
ULA5A1-9			0.03													0.03
ULA1A2-9			0.05													0.05
ULA3A2-4			0.05													0.05
ULA5A3			0.10													0.10
ULA2A3-4				0.05												0.05
ULA5A1-4				0.05												0.05
ULA2A3-9				0.05												0.05
ULA1A2-4				0.05												0.05
ULA3A2-9				0.05												0.05
ULA4A3				0.10												0.10
ULA2A4-4					0.05											0.05
ULA4A1-9					0.03											0.03
ULA2A4-9					0.05											0.05
ULA1A3-9					0.03											0.03
ULA3A3-4					0.05											0.05
ULA5A4					0.10											0.10
ULA2A5-4						0.03										0.03
ULA4A1-4						0.05										0.05
ULA1A3-4						0.05										0.05
ULA3A3-9						0.05										0.05
ULA4A4						0.10										0.10
ULA1A4-4							0.05									0.05
ULA3A4-4							0.05									0.05
ULA5A5							0.10									0.10
ULA1A5-9								0.02								0.02
ULA1A4-9								0.05								0.05
ULA3A4-9								0.05								0.05
ULA4A5								0.10								0.10
	CARD A3															
ULA2A5-9			0.05	0.05												0.05
ULA2A5-4			0.05	0.05												0.05
ULA3A4-9					0.05	0.05										0.05
ULA3A4-4					0.05	0.05										0.05
R-9									0.01							0.01
ULA4A1									0.10							0.10
ULA4A2									0.10							0.10
ULA3A2=9									0.05							0.05
ULA3A2-4									0.05							0.05
ULA3A3-9									0.05							0.05
ULA3A3-4									0.05							0.05
ULA3A5-9										0.05						0.05
ULA3A5-4										0.05						0.05
ULA2A1-9											0.05					0.05
ULA2A1-4											0.05					0.05
ULA2A2-9											0.05					0.05
ULA2A2-4											0.05					0.05
ULA2A3-9											0.05					0.05
ULA2A3-4											0.05					0.05
ULA2A4-9											0.05					0.05
ULA2A4-4											0.05					0.05
ULA3A1-9											0.05					0.05
ULA3A1-4											0.05					0.05
ULA1A1-9	0.05	0.05									0.05	0.05				0.05
ULA1A1-4	0.05	0.05									0.05	0.05				0.05

(continued)

Part Number	Symptom															
	Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
	CARD A3 (continued)															
ULA1A2-9			0.05	0.05							0.05		0.05			0.05
ULA1A2-4			0.05	0.05							0.05		0.05			0.05
ULA1A3-9									0.05		0.05			0.05		0.05
ULA1A3-4									0.05		0.05			0.05		0.05
ULA1A4-9							0.05	0.05			0.05				0.05	0.05
ULA1A4-4							0.05	0.05			0.05				0.05	0.05
CR1	0.015	0.015									0.015	0.015				0.015
CR2	0.015	0.015									0.015	0.015				0.015
CR3			0.015	0.015							0.015		0.015			0.015
CR4			0.015	0.015						0.015	0.015		0.015			0.015
CR5					0.015	0.015			0.015					0.015		0.015
CR6					0.015	0.015			0.015		0.015			0.015		0.015
CR7							0.015	0.015			0.015				0.015	0.015
CR8							0.015	0.015			0.015				0.015	0.015
ULA4A3	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10								0.10
ULA4A4-9	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
ULA4A4-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
R10	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01								0.01
C1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01								0.01
ULA4A-2	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05								0.05
	CARD A4															
Q3											0.10					0.10
CR3											0.015					0.015
Q1											0.10					0.10
CR1											0.015					0.015
Q8											0.10					0.10
CR8											0.015					0.015
Q5											0.10					0.10
CR6											0.015					0.015
Q6											0.10					0.10
CR5											0.015					0.015
Q7											0.10					0.10
CR7											0.015					0.015
Q4											0.10					0.10
CR4											0.015					0.015
Q2											0.10					0.10
CR2											0.015					0.015
Q9											0.10					0.10
CR9											0.015					0.015
ULA4A4-4											0.05					0.05
ULA3A4-9											0.05					0.05
ULA3A4-4											0.05					0.05
ULA1A5-4											0.05					0.05
ULA1A4-4											0.05					0.05
ULA4A1-9											0.05					0.05
ULA2A1-9											0.05					0.05
ULA2A1-4											0.05					0.05
ULA1A1-9											0.05					0.05
ULA4A1-4											0.05					0.05
ULA3A1-9											0.05					0.05
ULA3A1-4											0.05					0.05
ULA1A1-1											0.05					0.05
ULA4A2-9											0.05					0.05
ULA2A2-9											0.05					0.05
ULA2A2-4											0.05					0.05

(continued)

Part Number	Symptom															
	Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
	CARD A4 (continued)															
ULA1A2-9											0.05					0.05
ULA4A2-4											0.05					0.05
ULA3A2-9											0.05					0.05
ULA3A2-4											0.05					0.05
ULA1A2-4											0.05					0.05
ULA4A3-9											0.05					0.05
ULA2A3-9											0.05					0.05
ULA2A3-4											0.05					0.05
ULA1A3-9											0.05					0.05
ULA4A3-4											0.05					0.05
ULA3A3-9											0.05					0.05
ULA3A3-4											0.05					0.05
ULA1A3-4											0.05					0.05
ULA4A4-9											0.05					0.05
ULA2A4-4											0.05					0.05
ULA2A4-4											0.05					0.05
ULA1A4-9											0.05					0.05
ULA4A5-9											0.05					0.05
ULA2A5-9											0.05					0.05
ULA2A5-4											0.05					0.05
ULA1A5-4											0.05					0.05
	CARD A5															
R8			0.01	0.01												0.01
CR15			0.035	0.035												0.035
CR16			0.035	0.035												0.035
ULA4A4-9			0.05	0.05												0.05
ULA4A4-4			0.05	0.05												0.05
ULA4A3-4			0.05	0.05												0.05
ULA4A2-9			0.05	0.05												0.05
ULA4A3-9			0.05	0.05												0.05
ULA3A3-4			0.05	0.05												0.05
ULA3A3-9			0.05	0.05												0.05
CR22			0.035	0.035												0.035
Q2			0.10	0.10												0.10
R12			0.01	0.01												0.01
T2			0.40	0.40												0.40
R11			0.01	0.01												0.01
R13			0.01	0.01												0.01
CR21			0.05	0.05												0.05
CR20			0.05	0.05												0.05
CR19			0.035	0.035												0.035
ULA3A4-4			0.05	0.05												0.05
ULA3A4-9			0.05	0.05												0.05
R7			0.01	0.01												0.01
CR24			0.035	0.035												0.035
CR14			0.015	0.015												0.015
CR12			0.05	0.05												0.05
R9			0.01	0.01												0.01
CR13			0.05	0.05												0.05
CR17			0.015	0.015												0.015
CR18			0.035	0.035												0.035
R10			0.01	0.01												0.01
ULA3A1-4			0.05	0.05												0.05
ULA3A2-4			0.05	0.05												0.05
ULA3A1-9			0.05	0.05												0.05
ULA3A2-9			0.05	0.05												0.05

(continued)

Part Number	Symptom Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
CARD A5 (continued)																
R4					0.01	0.01										0.01
CR9					0.035	0.035										0.035
CR5					0.035	0.035										0.035
ULA2A4-9					0.05	0.05										0.05
ULA2A4-4					0.05	0.05										0.05
ULA2A3-4					0.05	0.05										0.05
ULA2A2-9					0.05	0.05										0.05
ULA2A3-9					0.05	0.05										0.05
ULA1A3-4					0.05	0.05										0.05
ULA1A3-9					0.05	0.05										0.05
CR4					0.035	0.035										0.035
Q1					0.10	0.10										0.10
R2					0.01	0.01										0.01
T1					0.40	0.40										0.40
R1					0.01	0.01										0.01
R14					0.01	0.01										0.01
CR3					0.05	0.05										0.05
CR2					0.05	0.05										0.05
CR1					0.035	0.035										0.035
ULA1A4-4					0.05	0.05										0.05
ULA1A4-9					0.05	0.05										0.05
R3					0.01	0.01										0.01
CR23					0.035	0.035										0.035
CR8					0.015	0.015										0.015
CR10					0.05	0.05										0.05
R5					0.01	0.01										0.01
CR11					0.05	0.05										0.05
CR6					0.015	0.015										0.015
CR7					0.035	0.035										0.035
R6					0.01	0.01										0.01
ULA1A1-4					0.05	0.05										0.05
ULA1A2-4					0.05	0.05										0.05
ULA1A1-9					0.05	0.05										0.05
ULA1A2-9					0.05	0.05										0.05
ULA4A1-4			0.05													0.05
ULA4A1-9				0.05												0.05
ULA2A1-4					0.05											0.05
ULA2A1-9						0.05										0.05
CARD A6																
Q1											0.10					0.10
CR1											0.05					0.05
R34											0.01					0.01
R13											0.01					0.01
R12											0.01					0.01
R11											0.01					0.01
R10											0.01					0.01
R22											0.01					0.01
R21											0.01					0.01
R20											0.01					0.01
R19											0.01					0.01
R18											0.01					0.01
R9											0.01					0.01
R8											0.01					0.01
R7											0.01					0.01

(continued)

Part Number	Symptom															
	Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
	CARD A6 (continued)															
R6											0.01					0.01
R27											0.01					0.01
R17											1.00					1.00
R26											0.01					0.01
R16											1.00					1.00
R25											0.01					0.01
R14											1.00					1.00
R24											0.01					0.01
R15											1.00					1.00
R23											0.01					0.01
R37											1.00					1.00
R28											0.01					0.01
R36											1.00					1.00
R33											0.01					0.01
R35											1.00					1.00
R32											0.01					0.01
R40											1.00					1.00
R31											0.01					0.01
R39											1.00					1.00
R30											0.01					0.01
R38											1.00					1.00
R1											0.01					0.01
R2											0.01					0.01
R3											0.01					0.01
R4											0.01					0.01
R5											0.01					0.01
	CARD A7															
R4							0.01	0.01								0.01
CR9							0.035	0.035								0.035
CR5							0.035	0.035								0.035
ULA2A4-9							0.05	0.05								0.05
ULA2A4-4							0.05	0.05								0.05
ULA2A3-4							0.05	0.05								0.05
ULA2A2-9							0.05	0.05								0.05
ULA2A3-9							0.05	0.05								0.05
ULA1A3-4							0.05	0.05								0.05
ULA1A3-9							0.05	0.05								0.05
CR4							0.035	0.035								0.035
Q1							0.10	0.10								0.10
R2							0.01	0.01								0.01
T1							0.40	0.40								0.40
R1							0.01	0.01								0.01
R14							0.01	0.01								0.01
CR3							0.05	0.05								0.05
CR2							0.05	0.05								0.05
CR1							0.035	0.035								0.035
ULA1A4-4							0.05	0.05								0.05
ULA1A4-9							0.05	0.05								0.05
R3							0.01	0.01								0.01
CR23							0.035	0.035								0.035
CR8							0.015	0.015								0.015
CR10							0.05	0.05								0.05
R5							0.01	0.01								0.01
CR11							0.05	0.05								0.05
CR6							0.015	0.015								0.015
CR7							0.035	0.035								0.035
R6							0.01	0.01								0.01
ULA1A1-4							0.05	0.05								0.05
ULA1A2-4							0.05	0.05								0.05

(continued)

Part Number	Symptom: Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
	CARD A7 (continued)															
ULA1A1-9							0.05	0.05								0.05
ULA1A2-9							0.05	0.05								0.05
R8	0.01	0.01														0.01
CR15	0.035	0.035														0.035
CR16	0.035	0.035														0.035
ULA4A4-9	0.05	0.05														0.05
ULA4A4-4	0.05	0.05														0.05
ULA4A3-4	0.05	0.05														0.05
ULA4A2-9	0.05	0.05														0.05
ULA4A3-9	0.05	0.05														0.05
ULA3A3-4	0.05	0.05														0.05
ULA3A3-9	0.05	0.05														0.05
CR22	0.035	0.035														0.035
Q2	0.10	0.10														0.10
R12	0.01	0.01														0.01
T2	0.40	0.40														0.40
R11	0.01	0.01														0.01
R13	0.01	0.01														0.01
CR21	0.05	0.05														0.05
CR20	0.05	0.05														0.05
CR19	0.035	0.035														0.035
ULA3A4-4	0.05	0.05														0.05
ULA3A4-9	0.05	0.05														0.05
R7	0.01	0.01														0.01
CR24	0.035	0.035														0.035
CR14	0.015	0.015														0.015
CR12	0.05	0.05														0.05
R9	0.01	0.01														0.01
CR13	0.05	0.05														0.05
CR17	0.015	0.015														0.015
CR18	0.035	0.035														0.035
R10	0.01	0.01														0.01
ULA3A1-4	0.05	0.05														0.05
ULA3A2-4	0.05	0.05														0.05
ULA3A1-9	0.05	0.05														0.05
ULA3A2-9	0.05	0.05														0.05
ULA4A1-4	0.05															0.05
ULA4A1-9		0.05														0.05
ULA2A1-4							0.05									0.05
ULA2A1-9								0.05								0.05
	CARD A8															
ULA1A1-9												0.05				0.05
ULA1A1-4												0.05				0.05
ULA1A2-9													0.05			0.05
ULA1A2-4													0.05			0.05
ULA1A3-9														0.05		0.05
ULA1A3-4														0.05		0.05
ULA1A4-9															0.05	0.05
ULA1A4-4															0.05	0.05
	CARD A9															
Q1							0.10	0.10								0.10
Q2							0.10	0.10								0.10
Q3							0.10	0.10								0.10
CR1							0.05	0.05								0.05
CR6							0.05	0.05								0.05
CR2							0.05	0.05								0.05
CR3							0.05	0.05								0.05

(continued)

Part Number	Symptom															
	Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
	CARD A9 (continued)															
CR4							0.05	0.05								0.05
CR5							0.05	0.05								0.05
ULA5A1-9							0.05	0.05								0.05
ULA5A2-4							0.05	0.05								0.05
ULA5A2-9							0.05	0.05								0.05
ULA5A5-9							0.05	0.05								0.05
ULA5A3-9							0.05	0.05								0.05
ULA5A4-9							0.05	0.05								0.05
ULA5A3-4							0.05	0.05								0.05
ULA5A4-4							0.05	0.05								0.05
ULA5A5-4							0.05	0.05								0.05
ULA4A3-9							0.05	0.05								0.05
ULA4A3-4							0.05	0.05								0.05
ULA4A1-9	0.05	0.05														0.05
ULA4A1-4	0.05	0.05														0.05
ULA3A1-9												0.05	0.05	0.05	0.05	0.05
ULA3A2												0.10	0.10	0.10	0.10	0.10
ULA2A3-4	0.05															0.05
ULA4A2-9	0.03															0.03
ULA2A2-4			0.05													0.05
ULA4A2-4		0.05														0.05
ULA2A2-9					0.05											0.05
ULA2A3-9							0.03									0.03
ULA2A4-9								0.05								0.05
ULA4A4-4							0.05									0.05
ULA4A4-9								0.03								0.03
ULA3A1-4	0.05		0.05		0.05		0.03	0.03								0.05
ULA3A3	0.10		0.10		0.10		0.06	0.06								0.10
	CARD A10															
Q4												0.10				0.10
Q3												0.10				0.10
Q2												0.10				0.10
Q1												0.10				0.10
Q8													0.10			0.10
Q7													0.10			0.10
Q6													0.10			0.10
Q5													0.10			0.10
ULA2A1-4												0.05				0.05
ULA2A2-4												0.05				0.05
ULA2A2-9												0.05				0.05
ULA2A1-9												0.05				0.05
ULA4A1-4													0.05			0.05
ULA4A2-4													0.05			0.05
ULA4A2-9													0.05			0.05
ULA4A1-9													0.05			0.05
ULA1A2												0.10				0.10
ULA2A5-9												0.05				0.05
ULA2A4-9												0.05				0.05
ULA2A3-9												0.05				0.05
ULA1A1												0.10				0.10
ULA1A3-4												0.05				0.05
ULA1A3-9												0.05				0.05
ULA1A4-9												0.05				0.05
ULA1A4-4												0.05				0.05
ULA3A2													0.10			0.10
ULA4A5-9													0.05			0.05
ULA4A4-9													0.05			0.05
ULA4A3-9													0.05			0.05
ULA3A1													0.10			0.10

(continued)

Part Number	Symptom															
	Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
CARD A10 (continued)																
ULA3A3-4													0.05			0.05
ULA3A3-9													0.05			0.05
ULA3A4-9													0.05			0.05
ULA3A4-4													0.05			0.05
ULA5A2														0.10		0.10
ULA5A3-4														0.05		0.05
ULA5A3-9														0.05		0.05
ULA5A4-9														0.05		0.05
ULA5A4-4														0.05		0.05
ULA5A2														0.10		0.10
CARD A11																
Q1					0.10	0.10										0.10
Q2					0.10	0.10										0.10
Q3					0.10	0.10										0.10
Q4			0.10	0.10												0.10
Q5			0.10	0.10												0.10
Q6			0.10	0.10												0.10
CR1					0.05	0.05										0.05
CR6					0.05	0.05										0.05
CR2					0.05	0.05										0.05
CR3					0.05	0.05										0.05
CR4					0.05	0.05										0.05
CR5					0.05	0.05										0.05
CR7			0.05	0.05												0.05
CR12			0.05	0.05												0.05
CR8			0.05	0.05												0.05
CR9			0.05	0.05												0.05
CR10			0.05	0.05												0.05
CR11			0.05	0.05												0.05
ULA2A1-4					0.05	0.05										0.05
ULA2A2-9					0.05	0.05										0.05
ULA2A2-4					0.05	0.05										0.05
ULA4A1-4			0.05	0.05												0.05
ULA4A2-9			0.05	0.05												0.05
ULA4A2-4			0.05	0.05												0.05
ULA1A2					0.10	0.10										0.10
ULA2A5-4					0.05	0.05										0.05
ULA2A4-4					0.05	0.05										0.05
ULA2A3-4					0.05	0.05										0.05
ULA1A1					0.10	0.10										0.10
ULA1A4-9					0.05	0.05										0.05
ULA1A4-4					0.05	0.05										0.05
ULA1A3-4					0.05	0.05										0.05
ULA1A3-9					0.05	0.05										0.05
ULA2A4-9					0.05	0.05										0.05
ULA2A3-9					0.05	0.05										0.05
ULA2A5-9					0.05	0.05										0.05
ULA3A2			0.10	0.10												0.10
ULA4A5-4			0.05	0.05												0.05
ULA4A4-4			0.05	0.05												0.05
ULA4A3-4			0.05	0.05												0.05
ULA3A1			0.10	0.10												0.10
ULA3A4-9			0.05	0.05												0.05
ULA3A4-4			0.05	0.05												0.05
ULA3A3-4			0.05	0.05												0.05

(continued)

Part Number	Symptom															
	Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
	CARD A11 (continued)															
ULA3A3-9			0.05	0.05												0.05
ULA4A4-9			0.05	0.05												0.05
ULA4A3-9			0.05	0.05												0.05
ULA4A5-9			0.05	0.05												0.05
ULA5A2							0.10	0.10								0.10
ULA5A1							0.10	0.10								0.10
ULA5A4-9							0.05	0.05								0.05
ULA5A4-4							0.05	0.05								0.05
ULA5A3-4							0.05	0.05								0.05
ULA5A3-9							0.05	0.05								0.05
	CARD A12															
Q7														0.10		0.10
Q8														0.10		0.10
Q9														0.10		0.10
Q10														0.10		0.10
Q2															0.10	0.10
Q1															0.10	0.10
Q3															0.10	0.10
Q4	0.10	0.10														0.10
Q5	0.10	0.10														0.10
Q6	0.10	0.10														0.10
ULA5A4-4														0.05		0.05
ULA5A5-4														0.05		0.05
ULA5A4-9														0.05		0.05
ULA5A5-9														0.05		0.05
ULA2A1-4															0.05	0.05
ULA2A2-4															0.05	0.05
ULA2A2-0															0.05	0.05
ULA4A1-4	0.05	0.05														0.05
ULA4A2-4	0.05	0.05														0.05
ULA4A2-9	0.05	0.05														0.05
ULA5A1-9														0.05		0.05
ULA5A3-9														0.05		0.05
ULA5A9-9														0.05		0.05
CR1															0.05	0.05
CR6															0.05	0.05
CR2															0.05	0.05
CR3															0.05	0.05
CR4															0.05	0.05
CR5															0.05	0.05
CR7	0.05	0.05														0.05
CR12	0.05	0.05														0.05
CR8	0.05	0.05														0.05
CR9	0.05	0.05														0.05
CR10	0.05	0.05														0.05
CR11	0.05	0.05														0.05
ULA1A2															0.10	0.10
ULA2A5-9															0.05	0.05
ULA2A4-9															0.05	0.05
ULA2A3-9															0.05	0.05
ULA1A1															0.10	0.10
ULA1A4-4															0.05	0.05
ULA1A4-9															0.05	0.05
ULA1A3-9															0.05	0.05
ULA1A3-4															0.05	0.05

(continued)

Part Number	Symptom															
	Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
	CARD A12 (continued)															
ULA2A4-4															0.05	0.05
ULA2A3-4															0.05	0.05
ULA2A5-4															0.05	0.05
ULA3A2	0.10	0.10														0.10
ULA4A5-9	0.05	0.05														0.05
ULA4A4-9	0.05	0.05														0.05
ULA4A3-9	0.05	0.05														0.05
ULA3A1	0.10	0.10														0.10
ULA3A4-4	0.05	0.05														0.05
ULA3A4-9	0.05	0.05														0.05
ULA3A3-9	0.05	0.05														0.05
ULA3A3-4	0.05	0.05														0.05
ULA4A4-4	0.05	0.05														0.05
ULA4A3-4	0.05	0.05														0.05
ULA4A5-4	0.05	0.05														0.05
	CARD A13															
Q17												0.10				0.10
CR37												0.035				0.035
Q18												0.10				0.10
CR38												0.035				0.035
Q19												0.10				0.10
CR39												0.035				0.035
Q20												0.10				0.10
CR40												0.035				0.035
Q21													0.10			0.10
CR41													0.035			0.035
Q22													0.10			0.10
CR42													0.035			0.035
Q23													0.10			0.10
CR43													0.035			0.035
Q24													0.10			0.10
CR44													0.035			0.035
Q13														0.10		0.10
CR25														0.035		0.035
Q14														0.10		0.10
CR26														0.035		0.035
Q15														0.10		0.10
CR27														0.035		0.035
Q16														0.10		0.10
CR28														0.035		0.035
Q4															0.10	0.10
CR8															0.035	0.035
Q8															0.10	0.10
CR12															0.035	0.035
Q12															0.10	0.10
CR24															0.035	0.035
Q1					0.10	0.10										0.10
CR5					0.035	0.035										0.035
Q5					0.10	0.10										0.10
CR9					0.035	0.035										0.035
Q9					0.10	0.10										0.10
CR21					0.035	0.035										0.035

(continued)

Part Number	Symptom															
	Incorrect Register Position 1	Incorrect Register Position 2	Incorrect Register Position 3	Incorrect Register Position 4	Incorrect Register Position 5	Incorrect Register Position 6	Incorrect Register Position 7	Incorrect Register Position 8	Incorrect To-From	Incorrect Camera Trigger	Incorrect Steering Deviation	Incorrect Range - Units	Incorrect Range - Tens	Incorrect Range - Hundreds	Incorrect Bearing	Total Failures
	CARD A13 (continued)															
Q2	0.10	0.10														0.10
CR6	0.035	0.035														0.035
Q6	0.10	0.10														0.10
CR10	0.035	0.035														0.035
Q10	0.10	0.10														0.10
CR22	0.035	0.035														0.035
Q3			0.10	0.10												0.10
CR7			0.035	0.035												0.035
Q7			0.10	0.10												0.10
CR11			0.035	0.035												0.035
Q11			0.10	0.10												0.10
CR23			0.035	0.035												0.035
Q25							0.10	0.10								0.10
CR52							0.035	0.035								0.035
Q26							0.10	0.10								0.10
CR53							0.035	0.035								0.035
Q27							0.10	0.10								0.10
CR54							0.035	0.035								0.035

APPENDIX II

REPARTITIONED CONFIGURATION OF THE INDICATOR COUPLER (AN/ARN-85)

New Card Number	Original Card Number	Part Numbers Transferred from Original to New Card Configuration
A5	A11	Q4, Q5, Q6, CR7, CR12, CR8, CR9, CR10, CR11, ULA4A1-4, ULA4A2-9, ULA4A2-4, ULA3A2, ULA4A5-4, ULA4A4-4, ULA4A3-4, ULA3A1, ULA3A4-9, ULA3A4-4, ULA3A3-4, ULA3A3-9, ULA4A4-9, ULA4A3-9, ULA4A5-9
	A13	Q3, CR7, Q7, CR11, Q11, CR23
A7	A11	ULA5A2, ULA5A1, ULA5A4-4, ULA5A4-9, ULA5A3-4, ULA5A3-9
	A13	Q25, CR52, Q26, CR53, Q27, CR54
A8	A10	Q4, Q3, Q2, Q1, ULA2A1-4, ULA2A2-4, ULA2A2-9 ULA2A1-9, ULA1A2, ULA2A5-9, ULA2A4-9, ULA2A3-9, ULA1A1, ULA1A3-4, ULA1A3-9, ULA1A4-9, ULA1A4-4
	A13	Q17, CR37, Q18, CR38, Q19, CR39, Q20, CR40
A10	A8	ULA1A2-9, ULA1A2-4
	A13	Q21, CR41, Q22, CR42, Q23, CR43, Q24, CR44
A11	A5	R4, CR9, CR5, ULA2A4-4, ULA2A4-9, ULA2A3-4, ULA2A2-9, ULA2A3-9, ULA1A3-4, ULA1A3-9, CR4, Q1, R2, T1, R1, R14, CR3, CR2, CR1, ULA1A4-4, ULA1A4-9, R3, CR23, CR8, CR10, R5, CR11, CR6, CR7, R6, ULA1A1-4, ULA1A2-4, ULA1A1-9, ULA1A2-9, ULA2A1-4, ULA2A1-9
	A13	Q1, CR5, Q5, CR9, Q9, CR21
A12	A7	R8, CR15, CR16, ULA4A4-9, ULA4A4-4, ULA4A3-4, ULA4A2-9, ULA4A3-9, ULA3A3-4, ULA3A3-9, CR22, Q2, R12, T2, R11, R13, CR21, CR20, CR19, ULA3A4-4, ULA3A4-9, R7, CR24, CR14, CR12, R9, CR13, CR17, CR18, R10, ULA3A1-4, ULA3A2-4, ULA3A1-9, ULA3A2-9, ULA4A1-4, ULA4A1-9
	A13	Q2, CR6, Q6, CR10, Q10, CR22

APPENDIX II (continued)

New Card Number	Original Card Number	Part Numbers Transferred from Original to New Card Configuration
A13	A8	ULA1A3-9, ULA1A3-4
	A10	ULA5A2, ULA5A3-4, ULA5A3-9, ULA5A4-9, ULA5A4-4
	A12	Q7, Q8, Q9, Q10, ULA5A4-4, ULA5A5-4, ULA5A4-9, ULA5A5-9, ULA5A1-9, ULA5A3-9, ULA5A9-9
A14	A8	ULA1A4-9, ULA1A4-4
	A12	Q2, Q1, Q3, ULA2A1-4, ULA2A2-4, ULA2A2-9, CR1, CR6, CR2, CR3, CR4, CR5, ULA1A2, ULA2A5-9, ULA2A4-9, ULA2A3-9, ULA1A1, ULA1A4, ULA1A4-9, ULA1A3-9, ULA1A3-4, ULA2A4-4, ULA2A3-4, ULA2A5-4
	A13	Q4, CR8, Q8, CR12, Q12, CR24

NOTE:

New Cards A1, A2, A3, A4, A6, and A9 remained the same as in the original configuration.

APPENDIX III

ANALYSIS TECHNIQUES FOR MICROELECTRONIC SYSTEM INTEGRATION AND PARTITIONING

INTRODUCTION

Increased integration of microelectronic circuits creates the problem of determining ideal integration and partitioning levels for specific operational and maintenance requirements (ref. 1, 2). This appendix describes a new application of combinatorial analysis and signal-graph theory for determining the best combination of possible partitioning and integration techniques, on the basis of minimum handling of signal lines (ref. 3, 4).

MICROELECTRONIC INTEGRATION AND SYSTEM PARTITIONING

In microelectronics, system integration is the process of converting interconnections of circuits and elements into intraconnections of function blocks with a set of partitioning constraints. System integration starts at the circuit level and proceeds to more complex functional levels through Medium-Scale Integration (MSI)* and Large-Scale Integration (LSI). Various integration techniques are being used or considered: Integrated Circuits (IC), MSI, and LSI.

The application of MSI and LSI to system design is a complex engineering problem because of the lack of proper tools for designing systems at a higher level than the circuit level, and the resulting large number of building-block types.

The impact of IC, MSI, and LSI has made partitioning and decomposition a problem for the device, circuit, and system designers. The partitioning problem is related to several

---

*See List of Symbols, Page v.

aspects of system design, and it deals with complexity levels, techniques to optimize function implementation, methods to minimize the handling of external signal lines by integration, diagnosis and fault location, system organization, and packaging.

To select an optimal partition, one must quantify and examine all possible alternatives. However, the possible number of partitions of n interacting blocks is large and increases rapidly as n increases. As a first step in partitioning, it is simpler to consider a smaller number of pertinent groups. This smaller number can be obtained by decomposing the set of n blocks into groups of integer summands and then selecting a subset of the decompositions for partitioning.

DECOMPOSITION AND PARTITIONING MODEL

System partitioning optimizes functional and structural block diagrams with respect to design objectives. A given system can be partitioned into different functional levels according to topology or function, or both. The selected partitioning levels are based on complexity of function and structure. This appendix considers the following complexity levels: system, subsystem, functional block, circuit, and element. Figure 4 relates the system partitioning levels to present integration methods (ref. 5). The following discussion presents an approach to system decomposition and partitioning, and a technique to evaluate and select an optimal partition with respect to a set of constraints.

To quantify the partitioning problem meaningfully, it is necessary to develop a mathematical model that supplies design information on grouping and partitioning. Combinatorial analysis and signal graph theory provide the desired tools to quantify the partitioning problem at a given complexity level (ref. 6, 7).

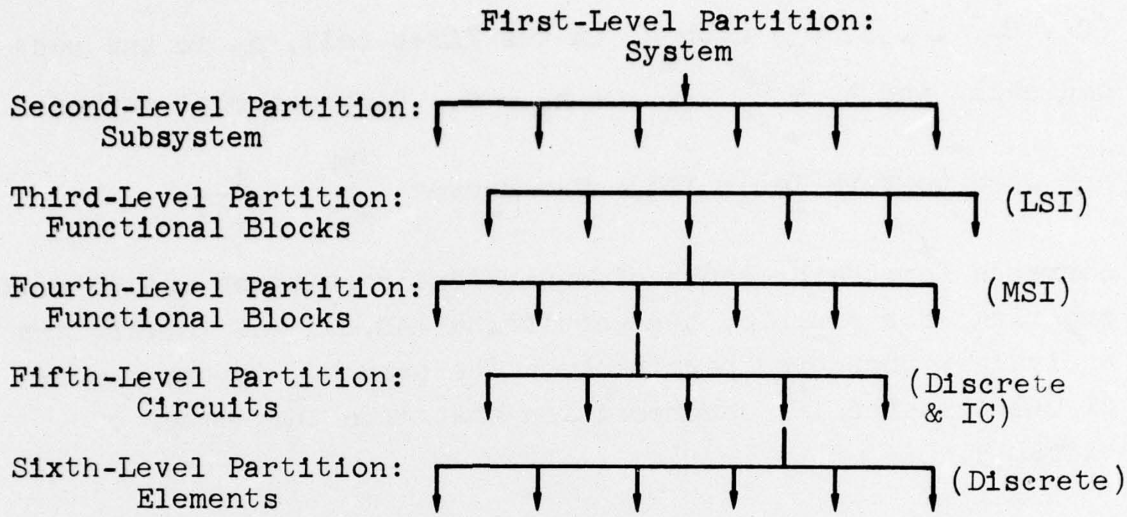


FIGURE 4

SUMMARY OF PARTITIONING LEVELS AND INTEGRATION TECHNIQUES

A set of n blocks can be decomposed in two ways: (1) unrestricted decompositions p(n) and (2) decompositions into distinct subsets q(n). The quantity p(n) is the number of decompositions of n into summands of positive integers without regard to order -- e.g., $4 = 1 + 3 = 2 + 2 = 1 + 1 + 2 = 1 + 1 + 2 = 1 + 1 + 1 + 1$, so that $p(4) = 5$. The quantity q(n) is the number of decompositions of n into summands of distinct positive integers without regard to order -- $5 = 1 + 4 = 2 + 3$ so that $q(5) = 3$ (See the first four columns of Table III.)

A partition of a set of n elements is a subdivision of the set into subsets that are disjoint and exhaustive. The subsets C_i in the partition are called cells, and the maximum number of nonempty cells within a partition is n.

A given decomposition can be partitioned in two ways with respect to cell order: ordered H_o and unordered H_n. Table III

gives H_o and H_n of a decomposition of n elements of r cells (C_1, C_2, . . ., C_r) with n_1 in the first cell, n_2 in the second cell, and $n_1 + n_2 \ldots + n_r = n$. Combinatorial methods are used to form Table III. The factor $\prod_{j=1}^{j=n} \frac{1}{h_{ij}!}$ corrects for the presence of equivalent partitions due to cell ordering; for example, the partitions [AB,CD] and [CD,AB] are equivalent unordered partitions. The term h_{ij} is the number of cells in the i^{th} decomposition that have the number of blocks j.

A direct approach to unordered partition counting can be achieved by using Stirling numbers of the second kind. $\mathfrak{S}_n^{(m)}$*, which gives the number of ways of partitioning a set of n elements into m nonempty cells, without regard to order, with $m \leq n$. Accordingly, the total number of unordered partitions H_t of a set of n elements is the sum of $\mathfrak{S}_n^{(m)}$ over m:

$$H_t = \sum_{m=1}^{m=n} \mathfrak{S}_n^{(m)} \tag{8}$$

In microelectronics, a cell may consist of one or more blocks, and cell ordering does not lead to distinguishable LSI structures. Therefore, unordered partition counting is applicable to LSI partitioning. Table III gives p(n), q(n), D_i corresponding decompositions, H_o, $\pi \frac{1}{h_{ij}!}$, H_n, m, $\mathfrak{S}_n^{(m)}$, and

*(See List of Symbols page v)

Table III
Decompositions and Partitions of n

n	p(n)	q(n)	Unrestricted Decompositions D_i	Ordered Partitions H_o	$\prod_{j=1}^{n} \frac{1}{h_{ij}!}$	Unordered Partitions H_n	m	$\mathfrak{S}_n^{(m)}$	Total Unordered Partitions H_t
1	1	1	(1)*	1	$\frac{1}{1!}$	1	1	1	1
2	2	1	(2)*	1	$\frac{1}{1!}$	1	1	1	2
			(1,1)	2	$\frac{1}{2!}$	1	2	1	
3	3	2	(3)*	1	$\frac{1}{1!}$	1	1	1	5
			(1,2)*	3	$\frac{1}{1!1!}$	3	2	3	
			(1,1,1)	6	$\frac{1}{3!}$	1	3	1	
4	5	2	(4)*	1	$\frac{1}{1!}$	1	1	1	15
			(1,3)*	4	$\frac{1}{1!1!}$	4	2	7	
			(2,2)	6	$\frac{1}{2!}$	3			
			(1,1,2)	12	$\frac{1}{2!1!}$	6	3	6	
			(1,1,1,1)	24	$\frac{1}{4!}$	1	4	1	
5	7	3	(5)*	1	$\frac{1}{1!}$	1	1	1	52
			(1,4)*	5	$\frac{1}{1!1!}$	5	2	15	
			(2,3)*	10	$\frac{1}{1!1!}$	10			
			(1,1,3)	20	$\frac{1}{2!1!}$	10	3	25	
			(1,2,2)	30	$\frac{1}{1!2!}$	15			
			(1,1,1,2)	60	$\frac{1}{3!1!}$	10	4	10	
			(1,1,1,1,1)	120	$\frac{1}{5!}$	1	5	1	
6	11	4	(6)*	1	$\frac{1}{1!}$	1	1	1	203
			(1,5)*	6	$\frac{1}{1!1!}$	6	2	31	
			(2,4)*	15	$\frac{1}{1!1!}$	15			
			(3,3)	20	$\frac{1}{2!}$	10			
			(1,1,4)	30	$\frac{1}{2!1!}$	15	3	90	
			(1,2,3)*	60	$\frac{1}{1!1!1!}$	60			
			(2,2,2)	90	$\frac{1}{3!}$	15			
			(1,1,1,3)	120	$\frac{1}{3!1!}$	20	4	65	
			(1,1,2,2)	180	$\frac{1}{2!2!}$	45			
			(1,1,1,1,2)	360	$\frac{1}{4!1!}$	15	5	15	
			(1,1,1,1,1,1)	720	$\frac{1}{6!}$	1	6	1	
7	15	5	(7)*	1	$\frac{1}{1!}$	1	1	1	877
			(1,6)*	7	$\frac{1}{1!1!}$	7	2	63	
			(2,5)*	21	$\frac{1}{1!1!}$	21			
			(3,4)*	35	$\frac{1}{1!1!}$	35			
			(1,1,5)	42	$\frac{1}{2!1!}$	21	3	301	
			(1,2,4)*	105	$\frac{1}{1!1!1!}$	105			
			(1,3,3)	140	$\frac{1}{1!2!}$	70			
			(2,2,3)	210	$\frac{1}{2!1!}$	105			
			(1,1,1,4)	210	$\frac{1}{3!1!}$	35	4	350	
			(1,1,2,3)	420	$\frac{1}{2!1!1!}$	210			
			(1,2,2,2)	630	$\frac{1}{1!3!}$	105			
			(1,1,1,1,3)	840	$\frac{1}{4!1!}$	35	5	140	
			(1,1,1,2,2)	1260	$\frac{1}{3!2!}$	105			
			(1,1,1,1,1,2)	2520	$\frac{1}{5!1!}$	21	6	21	
			(1,1,1,1,1,1,1)	5040	$\frac{1}{7!}$	1	7	1	

*Decompositions into distinct parts

H_t, and it shows that the number of unordered partitions increases at a high rate as n increases.

PARTITIONING PROCEDURE

For any complexity level, the following procedure comprises the partitioning steps for integrating a system with a set of partitioning constraints:

1. Decompose the set of blocks into groups, such as collections of interconnected circuits or function blocks.
2. Apply the partitioning constraints to all possible decompositions.
3. Use the block diagram, and partition the selected decompositions by a set of cuts.
4. Perform pin counting for each applicable partition by counting the crossed signal lines associated with each set of cuts of the block diagram or by using signal-lines-pair-combinations of the partitions.
5. Apply the constraints to the partitions, and use the total pin count to select an optimal partition.

The number of pins per LSI package can be obtained by counting the crossed signal lines enclosed within the corresponding set of cuts plus two pins (bias and ground). This method is tedious and leads to errors. Pins can be counted algebraically by using Signal-Lines-Pair-Combinations (SLPC), Isolated-Signal Lines (ISL), and the Total-Signal-Lines (TSL) of the blocks. $SLPC_i$ is the number of signal lines between block A_i and the remaining blocks, and $SLPC_{ij}$ is the number of signal lines connecting A_i with A_j. ISL_i is the number of signal lines associated with A_i only (not connected to any of the other blocks). TSL_i is the sum of $SLPC_i$ and ISL_i of A_i.

Consider a set of n interacting blocks, $A_1, A_2, \ldots, A_n$. It is desired to partition the set into subsets of m nonempty cells ($C_1, C_2, \ldots, C_m$) and count the pins associated with each cell, with n_1 blocks in the first cell, n_2 blocks in the second cell, etc., and $n_1 + n_2 + \ldots + n_m = n$. Each cell corresponds to one LSI package.

Let a_i be the TSL of A_i, a_ia_i be ISL of A_i, and a_ia_j be SLPC of A_i and A_j*. In equation form,

$$a_i = \sum_{j=1}^{j=n} a_ia_j = a_ia_1 + a_ia_2 + \ldots + a_ia_i + \ldots + a_ia_n$$

$$a_ia_i = a_i - \sum_{j=1, j\neq i}^{j=n} a_ia_j \tag{9}$$

The number of pins, P_1, required for C_1 to maintain communication with the remaining cells is (without bias and ground)

$$P_1 = \sum_{j=1}^{j=n_1} a_j - 2 \sum_{\substack{i,j=1 \\ i\neq j}}^{n_1} a_ia_j \tag{10}$$

The term $\sum_{i\neq j}^{n_1} a_ia_j$ is the number of interconnections converted to intraconnections.

Similarly, P_m of cell C_m is

$$P_m = \sum_{j=1}^{j=n_m} a_j - 2 \sum_{i\neq j}^{n_m} a_ia_j \tag{11}$$

*Subscript j refers to any of the blocks (A_1 to A_n) other than A_i.

or from Equation 10,

$$P_m = \sum_{i=1}^{n_m} a_i a_i + \sum_{i,j=1}^{i=n_m, j=n_1} a_i a_j + \ldots + \sum_{i=1, j=1}^{i=n_m, j=n_{m-1}} a_i a_j \quad (12)$$

The total number of pins, P_t, of partition $[C_1, C_2, \ldots, C_m]$ is

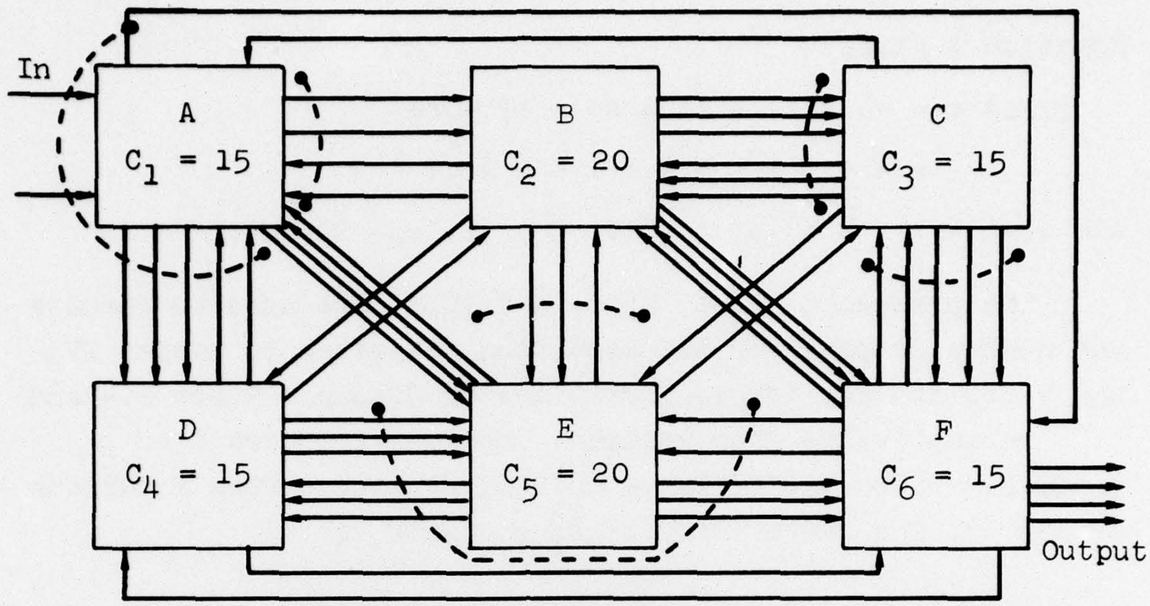
$$P_t = \sum_{k=1}^{k=m} P_k + 2m \quad (13)$$

EXAMPLE OF THE SELECTION OF OPTIMAL PARTITION

The preceding partitioning steps are best illustrated by an example. Consider the functional block shown in Figure 5 which consists of six interconnected function blocks. It is desired to partition the functional block for LSI with the following constraints:

1. Maximum number of circuits per LSI is 75.
2. Maximum number of pins per LSI package is 30.
3. Input Block A and Output Block F must not be in the same LSI package.
4. Maximum number of LSI packages is 2.

The number of unrestricted decompositions and unordered partitions of six blocks from Table III are 11 and 203, respectively. Accordingly, there are 203 alternatives for LSI partitioning of Figure 5. The first and last constraints eliminate all decompositions except 2,4 and 3,3. The second and third constraints will be used to select some partitions within the compatible decompositions. The number of unordered partitions within the decompositions 2,4 and 3,3 are 15 and 10,



$c = C_1, C_2 \ldots., C_6$ = Circuits

FIGURE 5

BLOCK DIAGRAM OF A FUNCTIONAL
BLOCK AND CUTS FOR PARTITION [ACE, BDF]

respectively, from Table III. Thus far, the number of LSI partitions to be considered is 25. Applying the third constraint reduces the number of applicable partitions to 25-7-4 = 14. The preceding analysis demonstrates how the constraints reduce the number of alternatives from 203 to 14.

The combinatorial technique of counting pins requires the determining of all pair combinations and the corresponding SLPC of the blocks. For 6 blocks, there are $\binom{6}{2}$ = 15 pair combinations.

From Figure 5, the SLPCs, ISLs, and TSLs are

$$(\text{SLPC})\begin{cases} ab = 4,\ ad = 5,\ af = 1,\ bd = 2,\ bf = 4,\ ce = 2,\ de = 6,\ ef = 5 \\ ac = 1,\ ae = 4,\ bc = 6,\ be = 3,\ cd = 0,\ cf = 5,\ df = 2 \end{cases}$$

(ISL) aa = 2, bb = 0, cc = 0, dd = 0, ee = 0, ff = 4

Equation 9 gives

$$(TSL)\ a = ab + ac + ad + ae + af + aa$$
$$= 4 + 1 + 5 + 4 + 1 + 2 = 17$$

and similarly, $b = 19$, $c = 14$, $d = 15$, $e = 20$, and $f = 21$

The preceding SLPCs, TSLs, and ISLs, are used to compute the number of pins per LSI partition, as given in Tables IV and V for the applicable partitions of decompositions 2,4 and 3,3, respectively. For example, consider LSI partition [ABCD,EF] where [ABCD] forms one LSI package. From Equations 12 and 13, the number of pins P_1 of [ABCD] is

$$P_1 = a + b + c + d - 2\ (ab+ac+ad+bc+bd+cd)$$
$$= 17 + 19 + 14 + 15 - 2\ (4+1+5+6+2+0)$$
$$= 29, \text{ from Equation 12}$$
$$= aa+bb+cc+dd+ae+af+be+bf+ce+cf+de+df$$
$$= 2 + 0 + 0 + 0 + 4 + 1 + 3 + 4 + 2 + 5 + 6 + 2$$
$$= 29, \text{ from Equation 13.}$$

Similarly, the number of pins P_2 of [EF] is

$$P_2 = e + f - 2\ (ef)$$
$$= 20 + 21 - 2\ (5)$$
$$= 31$$

The total number of pins, P_t, of LSI partition [ABCD,EF] is

$$P_t = P_1 + P_2 + 2\ (2)$$
$$= 29 + 31 + 4 = 64 \text{ pins,}$$

as given in Table IV. In Tables IV and V, the notation $\{N_1, N_2\}$ identifies the number of pins, including bias and ground pins, associated with LSI partition $\{C_1, C_2\}$.

From Tables IV and V, there are two partitions with the same number of pins, and both meet the specified constraints. The optimal partitions are [BCEF,AD] and [ADE,BCF].

TABLE IV

LSI Partitions and Evaluation for Decomposition (2,4)

L_1=106 L_2=257

LSI Partitions	Pins/LSI	Total Pins P_t
[ABCD,EF]	{31,33}	64
[ABCE,DF]	{32,34}	66
[ABDE,CF]	{25,27}	52
[ACDE,BF]	{32,34}	66
[BCDF,AE]	{33,31}	64
[BDEF,AC]	{33,31}	64
[BCEF,AD]	{26,24}	50
[CDEF,AB]	{32,30}	62

TABLE V

LSI Partitions and Evaluation for Decomposition (3,3)

[ABC,DEF]	{30,32}	62
[ABD,CEF]	{31,33}	64
[ABE,CDF]	{36,38}	74
[ACD,BEF]	{36,38}	74
[ACE,BDF]	{39,41}	80
[ADE,BCF]	{24,26}	50

CONCLUSIONS

Partitioning deals with many important aspects of system design, and it includes the problem of determining what should

be in an electronic package or on an LSI slice. System partitioning levels are considered complexity levels and are used to make partitioning problems tractable.

Systematic approaches are found to partition a collection of interacting electronic blocks and to count the number of pins per partition. Combinatorial analysis and signal-graph theory proved very useful in determining and selecting partitions, and in counting pins.

REFERENCES

1. "International Solid State Conference Digest", February 15-17, 1967, Philadelphia, Pa., pp 29-35, 44-54.

2. "Applications of Microelectronics Technology", Proceedings of the National Security Industrial Association and Air Force Systems Command, Washington, D.C., December 8-9, 1965.

3. J. Hartmanis, "On the State Assignment Problem for Sequential Machines I, II", IRE Transaction on Electronic Computers", June 1961, December 1961.

4. J. Dent, "Diagnostic Engineering", IEEE Spectrum, July, 1967, pp 99-104.

5. A. R. Habayeb, C. E. Holland, "Guideline Development for Alternative Microelectronic Approaches, Vol. 2, Applications", ARINC Research Corporation, Publication 527-11-11-767, May 1967.

6. J. G. Kemeny, J. L. Snell, G. L. Thompson, Introduction to Finite Mathematics, Prentice-Hall, Inc., 1957, pp 79-112.

7. M. Abramowitz, I. Stegum (editors), "Handbook of Mathematical Functions", National Bureau of Standards Applied Mathematics Series-55, U. S. Government Printing Office, Washington, D. C., 1964, pp 822-826.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 14 2930-929
2. GOVT ACCESSION NO.: 9 Technical rept. for Mar — Dec 67.
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): 6 PARTITIONING MICROELECTRONIC EQUIPMENT THROUGH THE USE OF A SYMPTOM MATRIX.
5. TYPE OF REPORT & PERIOD COVERED: 15 F33615-67-C-1517
6. PERFORMING ORG. REPORT NUMBER: 2930-929
7. AUTHOR(s): 10 Grafton H./Griswold Harold R./Leuba
8. CONTRACT OR GRANT NUMBER(s): Not Listed 12 65p
9. PERFORMING ORGANIZATION NAME AND ADDRESS: ARINC Research Corporation, 2551 Riva Road, Annapolis, Maryland 21401 16 7184 17 Ø9
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 11 Dec 67
11. CONTROLLING OFFICE NAME AND ADDRESS: Aerospace Medical Research Laboratories, Aerospace Medical Division, Air Force Systems Command
12. REPORT DATE: Not Listed
13. NUMBER OF PAGES: 32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Aerospace Medical Research Laboratories, Aerospace Medical Division, Air Force Systems Command
15. SECURITY CLASS. (of this report): UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report): UNCLASSIFIED/UNLIMITED
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
18. SUPPLEMENTARY NOTES
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this research was to establish the requirements for human-factors data to be used in the design of microelectronics. An interdisciplinary research team projected the design considerations that will be applicable during the period 1970-1980, and on the basis of these projections, postulated that the major human-factors-data requirements will be in the area of malfunction diagnosis. A feasibility study was initiated to determine feasibility of partitioning an equipment in such a way that the malfunction symptoms can be related directly to

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

400 247 Jen

a single or small group of replaceable assemblies. A symptom-matrix was prepared for a sample equipment (the Indicator-Coupler of the AN/ARN-85 LORAN Receiver) and then the equipment was repartitioned on the basis of the information contained in the matrix. A second matrix was prepared for the new configuration and then compared with the first matrix. It was found that the repartitioning had increased the amount of information provided by the symptom that could be used to identify the cause of the malfunction by 52 percent. It was concluded that this would reduce the number of errors that a maintenance technician would be likely to make in troubleshooting the reconfigured equipment.